USM-TH-78

Quark Structure of Λ from Λ-Polarization in Z Decays

Bo-Qiang Ma[a], Ivan Schmidt[b], and Jian-Jun Yang[b,c]

[a]CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, China
and Institute of High Energy Physics, Academia Sinica, P. O. Box 918(4),
Beijing 100039, China*
e-mail: mabq@hptc5.ihep.ac.cn

[b]Departamento de Física, Universidad Técnica Federico Santa María,
Casilla 110-V, Valparaíso, Chile
Email: ischmidt@fis.utfsm.cl

[c]Department of Physics, Nanjing Normal University,
Nanjing 210097, China
Email: jjyang@fis.utfsm.cl

Abstract

The flavor and spin structure for the quark distributions of the Λ-baryon is studied in a perturbative QCD (pQCD) analysis and in the SU(6) quark-diquark model, and then applied to calculate the Λ-polarization of semi-inclusive Λ production in e^+e^--annihilation near the Z-pole. It is found that the quark-diquark model gives very good description of the available experimental data. The pQCD model can also give good description of the data by taking into account the suppression of quark helicities compared to the naive SU(6) quark model spin distributions. Further information is required for a clean distinction between different predictions concerning the flavor and spin structure of the Λ.

PACS numbers: 14.20.Jn, 12.38.Bx, 12.39.Ki, 13.60.Hb

Version to be published in Phys. Rev. D 61 (2000).

*Mailing address

1 Introduction

The flavor and spin structure of the nucleons is one of the most active research directions of the high energy physics community. Though there have been remarkable achievements in our knowledge of the quark-gluon structure of the nucleons from three decades of experimental and theoretical investigations in various deep inelastic scattering (DIS) processes, the detailed flavor and spin structure of nucleons remains a domain with many unknowns, and there have been many unexpected surprises with respect to naive theoretical considerations. The sea content of the nucleons has received extensive investigations concerning its spin structure [1], strange content [3, 4], flavor asymmetry [2], and isospin symmetry breaking [5]. Even our knowledge of the valence quarks is still not well established, reflected from the recent investigations concerning the flavor and spin structure of the valence quarks for the nucleon near $x = 1$. For example, there are different predictions concerning the ratio $d(x)/u(x)$ at $x \to 1$ from the perturbative QCD (pQCD) analysis [6, 7] and the SU(6) quark-diquark model [8, 9, 10], and there are different predictions concerning the value of $F_2^n(x)/F_2^p(x)$ at large x, which has been taken to be 1/4 as in the quark-diquark model in most parameterizations of quark distributions. A recent analysis [11] of experimental data from several processes suggests that $F_2^n(x)/F_2^p(x) \to 3/7$ as $x \to 1$, in favor of the pQCD prediction. The spin structure of the valence quarks is also found to be different near $x = 1$ in these models, and predictions have been made concerning the non-dominant valence down (d) quark, so that $\Delta d(x)/d(x) = -1/3$ in the quark-diquark model [9, 10], a result which is different from the pQCD prediction $\Delta q(x)/q(x) = 1$ for either u and d [7]. At the moment, there is still no clear data in order to check these different predictions, although the available measurements [12] for the polarized d quark distributions seem to be negative at large x, slightly in favor of the quark-diquark model prediction.

It is important to perform high precision measurements of available physical quantities and/or to measure new quantities related to the flavor and spin structure of the nucleons, in order to reveal more about the quark-gluon structure of the nucleons. However, it should be more meaningful and efficient if we can find a new domain

where the same physics concerning the structure of the nucleons can manifest itself in a way that is more easy and clean to be detected and checked. It seems that Λ Physics is such a new frontier, and therefore can be used to test various ideas concerning the structure of the nucleons. It was found by Burkardt and Jaffe [13] that the u and d quarks inside a Λ should be negatively polarized from SU(3) symmetry. It was also pointed out by Soffer and one of us [14] that the flavor and spin content of the Λ can be used to test different predictions concerning the spin structure of the nucleon and the quark-antiquark asymmetry of the nucleon sea. Most recently, we found [15] that the flavor and spin structure of the Λ near $x = 1$ can provide clean tests between perturbative QCD (pQCD) and the SU(6) quark-diquark model predictions. We also found that the non-dominant up (u) and down (d) quarks should be positively polarized at large x, even though their net spin contributions to the Λ might be zero or negative. Thus it is clear that the quark structure of Λ is a frontier which can enrich our understanding concerning the flavor and spin structure of the nucleons and provides a new domain to test various ideas concerning the hadron structure that come from the available nucleon studies.

Unlike the nucleon case where the protons and neutrons (in the nuclei) can be used as targets in various DIS processes, direct measurement of the quark distributions of the Λ is difficulty, since the Λ is a charge-neutral particle which cannot be accelerated as incident beam and its short life time makes it also difficult to be used as a target. However, the quark distributions and the quark fragmentation functions are interrelated quantities that can uncover the structure of the involved hadron [16, 17]. For example, the quark distributions inside a hadron are related by crossing symmetry to the fragmentation functions of the same flavor quark to the same hadron, by a simple reciprocity relation [17]

$$q_h(x) \propto D_q^h(z), \tag{1}$$

where $z = 2p \cdot q/Q^2$ is the momentum fraction of the produced hadron from the quark jet in the fragmentation process, and $x = Q^2/2p \cdot q$ is the Bjorken scaling variable corresponding to the momentum fraction of the quark from the hadron in the DIS process. Although such a relation may be only valid at a specific scale Q^2

for $x \to 1$ and $z \to 1$ under leading order approximation and there are corrections to this relation from experimental observation and theoretical considerations [18], it can provide a reasonable connection between different physical quantities and lead to different predictions about the fragmentations based on our understanding of the quark structure of a hadron [14, 19]. Among the various possible hadrons that can be produced, Λ hyperon is most suitable for studying the polarized fragmentation due to its self-analyzing property owing to the characteristic decay mode $\Lambda \to p\pi^-$ with a large branching ratio of 64%. Thus we can use various Λ fragmentation processes to investigate the spin and flavor structure of the Λ and to test various ideas concerning the hadron structure. From another point of view, studying the quark to Λ fragmentations is also interesting in itself. We may consider our study as a phenomenological method to parameterize the quark to Λ fragmentation functions, and the validity and reasonableness of the method can be checked by comparison with the experimental data on various quark to Λ fragmentation functions.

There have been many proposals concerning the measurements of the Λ fragmentations functions in different processes, for different physical goals [13-15,18-27], and in this paper we will focus our attention on the longitudinally polarized case. One promising method to obtain a complete set of polarized fragmentation functions for different quark flavors is based on the measurement of the helicity asymmetry for semi-inclusive production of Λ hyperons in e^+e^- annihilation on the Z^0 resonance [13]. Measurements of the light-flavor quark fragmentations into Λ have been also suggested from polarized electron DIS process [23] and neutrino DIS process [25], based on the u-quark dominance assumption. It has been also suggested to determine the polarized fragmentation functions by measuring the helicity transfer asymmetry in the process $p\overrightarrow{p} \to \overrightarrow{\Lambda} X$ [26]. From its dependence on the rapidity of the Λ, it is possible to discriminate between various parameterizations. There is also a recent suggestion [14] to measure a complete set of quark to Λ unpolarized and polarized fragmentation functions for different quark flavors by the systematic exploitation of unpolarized and polarized Λ and $\overline{\Lambda}$ productions in neutrino, antineutrino and polarized electron DIS processes.

Recently there have been detailed measurements of the Λ polarizations from the

Z decays in e^+e^--annihilation [30, 31, 32]. The measured Λ-polarization has been compared with several theoretical calculations [25, 27, 28] based on simple ansatz such as $\Delta D_q^\Lambda(z) = C_q(z) D_q^\Lambda(z)$ with constant coefficients C_q, or Monte Carlo event generators without a clear physical motivation. It is the purpose of this paper to calculate the Λ-polarization in e^+e^--annihilation at the Z-pole by using the physics results presented in Ref. [15]. It will be shown that the quark-diquark model gives a very good description of the available experimental data; pQCD can also give a good description of the data by taking into account the suppression of quark helicities compared to the SU(6) quark model values of quark spin distributions. Thus the prediction of positive polarizations for the u and d quarks inside the Λ at $x \to 1$ is supported by the available experimental data.

The paper is organized as follows. In Section II of the paper we will present the formulas for the Λ-polarization in the e^+e^--annihilation near the Z-pole. In Section III we calculate the Λ-polarization in the SU(6) quark-diquark model and find that the model gives a very good description of the available data. In Section IV we present the analysis for three cases in the pQCD framework and find that we can also give a good description of the data by taking into account the suppression of quark helicities compared to the naive SU(6) quark model spin distributions. Finally, we present discussions and conclusions in Section V.

2 Λ-Polarization in e^+e^--Annihilation near the Z-Pole

One interesting feature of quark-antiquark ($q\overline{q}$) production in e^+e^--annihilation near the Z-pole is that the produced quarks (antiquarks) are polarized due to the interference between the vector and axial vector couplings in the standard model of electroweak interactions, even though the initial e^+ and e^- beams are unpolarized. Such quark (antiquark) polarization leads to the polarization of the Λ ($\overline{\Lambda}$) from the decays of the quarks, therefore we can study the polarized quark to Λ fragmentations by the semi-inclusive production of Λ in e^+e^--annihilation near the Z-pole [13, 20, 27, 28].

The differential cross section for the $e^+e^- \to q\overline{q}$ process near the Z-pole is

$$\begin{aligned}
\frac{d\sigma}{d\Omega} &= N_c \frac{\alpha^2(Q^2)}{4s} \Big\{(1+\cos^2\theta)[e_q^2 - 2\chi_1 v_e v_q e_q + \chi_2 (a_e^2+v_e^2)(a_q^2+v_q^2)] \\
&+ 2\cos\theta[-2\chi_1 a_e a_q e_q + 4\chi_2 a_e a_q v_e v_q]\Big\} ,
\end{aligned} \tag{2}$$

where

$$\chi_1 = \frac{1}{16\sin^2\theta_W\cos^2\theta_W}\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}, \tag{3}$$

$$\chi_2 = \frac{1}{256\sin^4\theta_W\cos^4\theta_W}\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}, \tag{4}$$

$$a_e = -1 \tag{5}$$

$$v_e = -1 + 4\sin^2\theta_W \tag{6}$$

$$a_q = 2T_{3q}, \tag{7}$$

$$v_q = 2T_{3q} - 4e_q\sin^2\theta_W, \tag{8}$$

where $T_{3q} = 1/2$ for u, c, while $T_{3q} = -1/2$ for d, s, b quarks, $N_c = 3$ is the color number, e_q is the charge of the quark in units of the proton charge, θ is the angle between the outgoing quark and the incoming electron, θ_W is the Weinberg angle, and M_Z and Γ_Z are the mass and width of Z^0.

In the parton-quark model, the differential cross section for the semi-inclusive hadron (h) production process $e^+e^- \to h+X$ is obtained by summing over the above cross section, weighted with the probability $D_q^h(z,Q^2)$ that a quark with momentum P/z fragments into a hadron h with momentum P,

$$\frac{d^2\sigma^h}{d\Omega dz} = \sum_q \frac{d\sigma}{d\Omega} D_q^h(z,Q^2), \tag{9}$$

where the $D_q^h(z,Q^2)$ are normalized so that

$$\sum_h \int z D_q^h(z,Q^2)\mathrm{d}z = 1. \tag{10}$$

The corresponding cross section for the production of polarized hadron h production can be written as [13]

$$\begin{aligned}
\frac{d^2\Delta\sigma}{d\Omega dz} &= -N_c\frac{\alpha^2(Q^2)}{2s}\sum_q \Big\{-e_q\chi_1\{a_q v_e[\Delta D_q^h(z) - \Delta D_{\overline{q}}^h(z)](1+\cos^2\theta) \\
&+ 2a_e v_q[\Delta D_q^h(z) + \Delta D_{\overline{q}}^h(z)]\cos\theta\} \\
&+ \chi_2\{(v_e^2+a_e^2)v_q a_q[\Delta D_q^h(z) - \Delta D_{\overline{q}}^h(z)](1+\cos^2\theta) \\
&+ 2v_e a_e(v_q^2+a_q^2)[\Delta D_q^h(z) + \Delta D_{\overline{q}}^h(z)]\cos\theta\}\Big\} .
\end{aligned} \tag{11}$$

The polarizations of the initial quarks from e^+e^--annihilation are given by

$$P_q = -\frac{A_q(1+\cos^2\theta) + B_q\cos\theta}{C_q(1+\cos^2\theta) + D_q\cos\theta}, \tag{12}$$

where

$$A_q = 2\chi_2(v_e^2 + a_e^2)v_q a_q - 2e_q\chi_1 a_q v_e, \tag{13}$$

$$B_q = 4\chi_2 v_e a_e(v_q^2 + a_q^2) - 4e_q\chi_1 a_e v_q, \tag{14}$$

$$C_q = e_q^2 - 2\chi_1 v_e v_q e_q + \chi_2(a_e^2 + v_e^2)(a_q^2 + v_q^2), \tag{15}$$

$$D_q = 8\chi_2 a_e a_q v_e v_q - 4\chi_1 a_e a_q e_q. \tag{16}$$

Averaging over θ, one obtains $P_q = -0.67$ for $q = u$, c, and $P_q = -0.94$ for $q = d$, s, and b at the Z-pole. From the cross section formulas for the unpolarized and polarized h production, we can write the formula for the Λ-polarization

$$P_\Lambda(\theta) = -\frac{\sum\limits_q \left\{A_q(1+\cos^2\theta)[\Delta D_q^h(z) - \Delta D_{\overline{q}}^h(z)] + B_q\cos\theta[\Delta D_q^h(z) + \Delta D_{\overline{q}}^h(z)]\right\}}{\sum\limits_q \left\{C_q(1+\cos^2\theta)[D_q^h(z) + D_{\overline{q}}^h(z)] + D_q\cos\theta[D_q^h(z) + D_{\overline{q}}^h(z)]\right\}}. \tag{17}$$

By averaging over θ we obtain

$$P_\Lambda = -\frac{\sum\limits_q A_q[\Delta D_q^h(z) - \Delta D_{\overline{q}}^h(z)]}{\sum\limits_q C_q[D_q^h(z) + D_{\overline{q}}^h(z)]}. \tag{18}$$

There have been measurements of the Λ-polarization near the Z-pole [30, 31, 32]. The ALEPH collaboration [30] measured the Λ-polarization by combining data of both Λ and $\overline{\Lambda}$. Since the $\overline{q}$ quark helicity is expected to be opposite that of the q quark, the identical polarization P_Λ is assumed for either Λ and $\overline{\Lambda}$ in the treatment of the data. Therefore we can consider their data as P_Λ for Λ production by Eq. (18). From Eq. (18) it can be found that we need both the quark and anti-quark distributions to calculate the Λ-polarization P_Λ at all x. However, the main purpose of this paper aims at checking the flavor and spin structure of the Λ at large x predicted in Ref. [15], thus we neglect the contribution from the sea quarks in our calculations of the Λ-polarization in the following discussions.

3 Λ-Polarization in the SU(6) Quark-Diquark Model

Before we look into the details of the flavor and spin structure for the valence quarks of the Λ, we briefly review the analysis of the unpolarized and polarized quark distributions in light-cone SU(6) quark-spectator-diquark model [9], which can be considered as a revised version of the original SU(6) quark-diquark models [8]. The light-cone formalism provides a convenient framework for the relativistic description of hadrons in terms of quark and gluon degrees of freedom [33, 34, 35]. Light-cone quantization has a number of unique features that make it appealing, most notably, the ground state of the free theory is also a ground state of the full theory, and the Fock expansion constructed on this vacuum state provides a complete relativistic many-particle basis for diagonalizing the full theory [36].

As we know, it is proper to describe deep inelastic scattering as the sum of incoherent scatterings of the incident lepton on the partons in the infinite momentum frame or in the light-cone formalism. The unpolarized valence quark distributions $u_v(x)$ and $d_v(x)$ are given in this model by

$$\begin{aligned} u_v(x) &= \frac{1}{2}a_S(x) + \frac{1}{6}a_V(x); \\ d_v(x) &= \frac{1}{3}a_V(x), \end{aligned} \tag{19}$$

where $a_D(x)$ ($D = S$ for scalar spectator or V for axial vector spectator) is normalized such that $\int_0^1 \mathrm{d}x a_D(x) = 3$, and it denotes the amplitude for quark q to be scattered while the spectator is in the diquark state D. Exact SU(6) symmetry provides the relation $a_S(x) = a_V(x)$, which implies the valence flavor symmetry $u_v(x) = 2d_v(x)$. This gives the prediction $F_2^n(x)/F_2^p(x) \geq 2/3$ for all x, which is ruled out by the experimental observation $F_2^n(x)/F_2^p(x) < 1/2$ for $x \to 1$. The SU(6) quark-diquark model [8] introduces a breaking to the exact SU(6) symmetry by the mass difference between the scalar and vector diquarks and predicts $d(x)/u(x) \to 0$ at $x \to 1$, leading to a ratio $F_2^n(x)/F_2^p(x) \to 1/4$, which could fit the data and has been accepted in most parameterizations of quark distributions for the nucleon. It has been shown that the SU(6) quark-spectator-diquark model can reproduce the u and d valence quark asymmetry that accounts for the observed ratio $F_2^n(x)/F_2^p(x)$ at large x [9].

This supports the quark-spectator picture of deep inelastic scattering in which the difference between the mass of the scalar and vector spectators is essential in order to reproduce the explicit SU(6) symmetry breaking while the bulk SU(6) symmetry of the quark model still holds.

The quark helicity distributions for the u and d quarks can be written as [9]

$$\begin{aligned} \Delta u_v(x) &= u_v^{\uparrow}(x) - u_v^{\downarrow}(x) = -\tfrac{1}{18} a_V(x) W_q^V(x) + \tfrac{1}{2} a_S(x) W_q^S(x); \\ \Delta d_v(x) &= d_v^{\uparrow}(x) - d_v^{\downarrow}(x) = -\tfrac{1}{9} a_V(x) W_q^V(x), \end{aligned} \tag{20}$$

in which $W_q^S(x)$ and $W_q^V(x)$ are the Melosh-Wigner correction factors [9, 37, 38] for the scalar and axial vector spectator-diquark cases. They are obtained by averaging Eq. (21) over $\mathbf{k}_\perp$ with $k^+ = x\mathcal{M}$ and $\mathcal{M}^2 = \frac{m_q^2+\mathbf{k}_\perp^2}{x} + \frac{m_D^2+\mathbf{k}_\perp^2}{1-x}$, where m_D is the mass of the diquark spectator, and are unequal due to unequal spectator masses, which leads to unequal $\mathbf{k}_\perp$ distributions. The explicit expression for the Melosh-Wigner rotation factor [37] is

$$W_q(x, \mathbf{k}_\perp) = \frac{(k^+ + m)^2 - \mathbf{k}_\perp^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2}, \tag{21}$$

which ranges between $0 \to 1$ due to the quark intrinsic transverse motions. From Eq. (19) one gets

$$\begin{aligned} a_S(x) &= 2u_v(x) - d_v(x); \\ a_V(x) &= 3d_v(x). \end{aligned} \tag{22}$$

Combining Eqs. (20) and (22) we have

$$\begin{aligned} \Delta u_v(x) &= [u_v(x) - \frac{1}{2} d_v(x)] W_q^S(x) - \frac{1}{6} d_v(x) W_q^V(x); \\ \Delta d_v(x) &= -\frac{1}{3} d_v(x) W_q^V(x). \end{aligned} \tag{23}$$

Thus we arrive at simple relations [9] between the polarized and unpolarized quark distributions for the valence u and d quarks. The relations (23) can be considered as the results of the conventional SU(6) quark model, and which explicitly take into account the Melosh-Wigner rotation effect [37] and the flavor asymmetry introduced by the mass difference between the scalar and vector spectators [9]. The calculated polarization asymmetries $A_1^N = 2xg_1^N(x)/F_2^N(x)$, including the Melosh-Wigner rotation, have been found [9] to be in reasonable agreement with the experimental data,

at least for $x \geq 0.1$. A large asymmetry between $W_q^S(x)$ and $W_q^V(x)$ leads to a better fit to the data than that obtained from a small asymmetry.

One interesting feature predicted from the relation is that $\Delta u(x)/u(x) \to 1$ and $\Delta d(x)/d(x) \to -1/3$ at $x \to 1$. The prediction $\Delta d(x)/d(x) \to -1/3$ is different from the pQCD prediction $\Delta d(x)/d(x) \to 1$ at large x, and with the available data it is still not possible to make a clear distinction between the two predictions. Thus the $\Delta d(x)/d(x)$ behavior at $x \to 1$ can provide a new test between pQCD and the quark-diquark model predictions.

In the following we analyze the valence quark distributions of the Λ by extending the SU(6) quark-spectator-diquark model [9] from the nucleon case to the Λ. The Λ wave function in the conventional SU(6) quark model is written as

$$|\Lambda^{\uparrow}\rangle = \frac{1}{2\sqrt{3}}[(u^{\uparrow}d^{\downarrow} + d^{\downarrow}u^{\uparrow}) - (u^{\downarrow}d^{\uparrow} + d^{\uparrow}u^{\downarrow})]s^{\uparrow} + (\text{cyclic} \quad \text{permutation}). \tag{24}$$

The SU(6) quark-diquark model wave function for the Λ is written as

$$\Psi_{\Lambda}^{\uparrow,\downarrow} = \sin\theta \; \varphi_V |qV\rangle^{\uparrow,\downarrow} + \cos\theta \; \varphi_S |qS\rangle^{\uparrow,\downarrow}, \tag{25}$$

with

$$\begin{aligned} |qV\rangle^{\uparrow,\downarrow} &= \pm\tfrac{1}{\sqrt{6}}[V_0(ds)u^{\uparrow,\downarrow} - V_0(us)d^{\uparrow,\downarrow} - \sqrt{2}V_{\pm}(ds)u^{\downarrow,\uparrow} + \sqrt{2}V_{\pm}(us)d^{\downarrow,\uparrow}]; \\ |qS\rangle^{\uparrow,\downarrow} &= \tfrac{1}{\sqrt{6}}[S(ds)u^{\uparrow,\downarrow} + S(us)d^{\uparrow,\downarrow} - 2S(ud)s^{\uparrow,\downarrow}], \end{aligned} \tag{26}$$

where $V_{s_z}(q_1q_2)$ stands for a q_1q_2 vector diquark Fock state with third spin component s_z, $S(q_1q_2)$ stands for a q_1q_2 scalar diquark Fock state, and φ_D stands for the momentum space wave function of the quark-diquark with D representing the vector (V) or scalar (S) diquarks. The angle θ is a mixing angle that breaks the SU(6) symmetry at $\theta \neq \pi/4$ and in this paper we choose the bulk SU(6) symmetry case $\theta = \pi/4$.

From Eq. (25) we get the unpolarized quark distributions for the three valence u, d, and s quarks for the Λ,

$$\begin{aligned} &u_v(x) = d_v(x) = \tfrac{1}{4}a_{V(qs)}(x) + \tfrac{1}{12}a_{S(qs)}(x); \\ &s_v(x) = \tfrac{1}{3}a_{S(ud)}(x), \end{aligned} \tag{27}$$

where $a_{D(q_1q_2)}(x) \propto \int[\mathrm{d}^2\vec{\mathrm{k}}_{\perp}]|\varphi(\mathrm{x}, \vec{\mathrm{k}}_{\perp})|^2$ ($D = S$ or V) denotes the amplitude for the quark q being scattered while the spectator is in the diquark state D, and is normalized

such that $\int_0^1 a_{D(q_1q_2)}(x)\mathrm{dx} = 3$. We assume the u and d symmetry $D(qs) = D(us) = D(ds)$, from the u and d symmetry inside Λ.

We get from Eq. (25) the spin distribution probabilities in the quark-diquark model

$$\begin{array}{ll} u_V^{\uparrow} = d_V^{\uparrow} = 1/12; & u_V^{\downarrow} = d_V^{\downarrow} = 1/6; \\ u_S^{\uparrow} = d_S^{\uparrow} = 1/12; & u_S^{\downarrow} = d_S^{\downarrow} = 0; \\ s_V^{\uparrow} = 0; & s_V^{\downarrow} = 0; \\ s_S^{\uparrow} = 1/3; & s_S^{\downarrow} = 0; \end{array} \tag{28}$$

Similar to the nucleon case, the quark spin distributions for the three valence quarks can be expressed as,

$$\begin{array}{l} \Delta u_v(x) = \Delta d_v(x) = -\frac{1}{12} a_{V(qs)}(x) W_{V(qs)}(x) + \frac{1}{12} a_{S(qs)}(x) W_{S(qs)}(x); \\ \Delta s_v(x) = \frac{1}{3} a_{S(ud)}(x) W_{S(ud)}(x), \end{array} \tag{29}$$

where $W_D(x)$ is the correction factor due to the Melosh-Wigner rotation and is expressed as

$$W_{D(q_1q_2)}(x) = \int [\mathrm{d}^2\vec{\mathrm{k}}_\perp] \mathrm{W}_{\mathrm{D}(\mathrm{q}_1\mathrm{q}_2)}(\mathrm{x})(\mathrm{x}, \vec{\mathrm{k}}_\perp) |\varphi(\mathrm{x}, \vec{\mathrm{k}}_\perp)|^2 / \mathrm{a}_{\mathrm{D}(\mathrm{q}_1\mathrm{q}_2)}(\mathrm{x}). \tag{30}$$

One can turn off the Melosh-Wigner rotation effect by setting $W_D(x) = 1$, which should be only true at $x \to 1$. This case was discussed in Ref. [15].

In order to perform the calculation, we employ the Brodsky-Huang-Lepage (BHL) prescription [35] of the light-cone momentum space wave function for the quark-spectator

$$\varphi(x, \vec{k}_\perp) = A_D \exp\{-\frac{1}{8\alpha_D^2}[\frac{m_q^2 + \vec{k}_\perp^2}{x} + \frac{m_D^2 + \vec{k}_\perp^2}{1-x}]\}, \tag{31}$$

with parameters (in units of MeV) $m_q = 330$ for $q = u$ and d, $m_s = 480$, $\alpha_D = 330$, $m_{S(ud)} = 600$, $m_{S(qs)} = 750$, and $m_{V(qs)} = 950$, following Ref. [9]. The differences in the diquark masses $m_{S(ud)}$, $m_{S(qs)}$, and $m_{V(qs)}$ cause the symmetry breaking between $a_{D(q_1q_2)}(x)$ in a way that $a_{S(ud)}(x) > a_{S(qs)}(x) > a_{V(qs)}(x)$ at large x.

In Fig. 1 we present the ratio $u(x)/s(x)$ calculated from the quark-diquark model. We also present in Fig. 2 the ratio $\Delta s(x)/s(x)$ for the dominant valence s quark which provides the quantum numbers of strangeness and spin of the Λ , and the ratio $\Delta u(x)/u(x)$ for the non-dominant valence u and d quarks. We find that the ratio

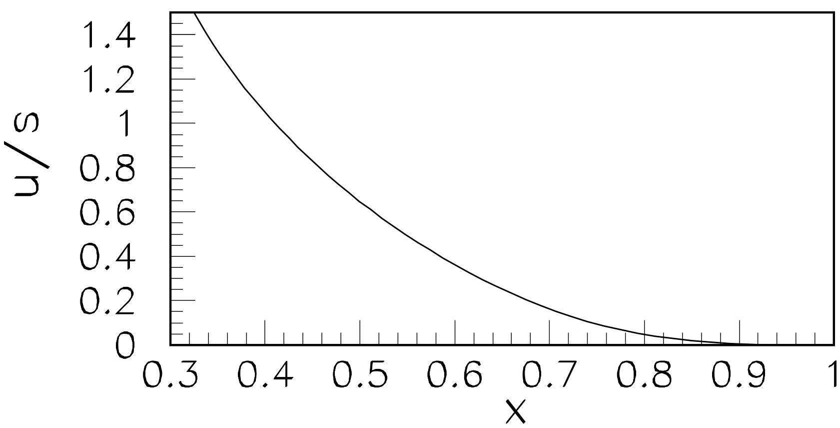

Figure 1: The ratio $u(x)/s(x)$ of the Λ in the SU(6) quark-diquark model.

$\Delta s(x)/s(x)$ is not a constant equal to 1 as is the case without Melosh-Wigner rotation. The ratio $\Delta u(x)/u(x)$, presented in Fig. 3, is also suppressed at $x \neq 1$. But the end-point behaviors at $x \to 1$ is unchanged. Thus the quark-diquark model predicts, in the limit $x \to 1$, that $u(x)/s(x) \to 0$ for the unpolarized quark distributions, $\Delta s(x)/s(x) \to 1$ for the dominant valence s quark, and also $\Delta u(x)/u(x) \to 1$ for the non-dominant valence u and d quarks.

In Fig. 4 we present our calculated result for the Λ-polarization $P_\Lambda(z)$ and we find that the theoretical results from the quark-diquark model fit the data very well within its present precision, at least in the large z region. Thus the quark-diquark model provides a successful description of the Λ-polarization $P_\Lambda(z)$, in addition to its successful descriptions of the ratio $F_2^n(x)/F_2^p(x)$ and the polarized structure functions for the proton and neutron. It is necessary to point out that the quark-diquark model with simple wave functions such as the BHL prescription can provide good descriptions of the relations between different quantities where the uncertainties in the model can be canceled between each other. It is impractical to expect a good description of the absolute magnitude and shape for a basic physical quantity, such as the detailed feature of the cross section, within such a model with simple wave functions. In fact there have been calculations of the explicit shapes for the quark fragmentation functions in a quark-diquark model [39] and for the quark distributions

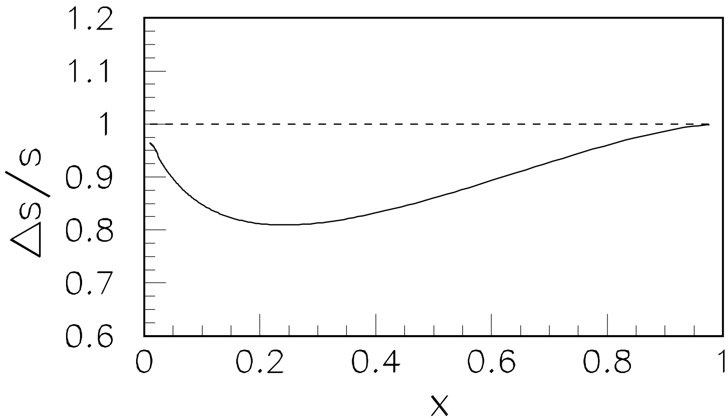

Figure 2: The ratio $\Delta s(x)/s(x)$ for the valence strange quark of the Λ in the SU(6) quark-diquark model. The solid and dotted curves are the corresponding results with (solid) and without (dotted) the Melosh-Wigner rotation.

inside the Λ in the MIT bag model [40]. We are very interested to notice that the two works arrived at the same qualitative conclusion as ours for a positive u and d polarization inside Λ at large x with small magnitude, though there are some difference in detailed quantitative features.

4 Λ-Polarization in pQCD Analysis

We now look at the pQCD analysis of the quark distributions. In the region $x \to 1$ pQCD can give rigorous predictions for the behavior of distribution functions [7]. In particular, it predicts "helicity retention", which means that the helicity of a valence quark will match that of the parent nucleon. Explicitly, the quark distributions of a hadron h have been shown to satisfy the counting rule [41],

$$q_h(x) \sim (1-x)^p, \tag{32}$$

where

$$p = 2n - 1 + 2\Delta S_z. \tag{33}$$

Here n is the minimal number of the spectator quarks, and $\Delta S_z = |S_z^q - S_z^h| = 0$ or 1 for parallel or anti-parallel quark and hadron helicities, respectively [7]. With

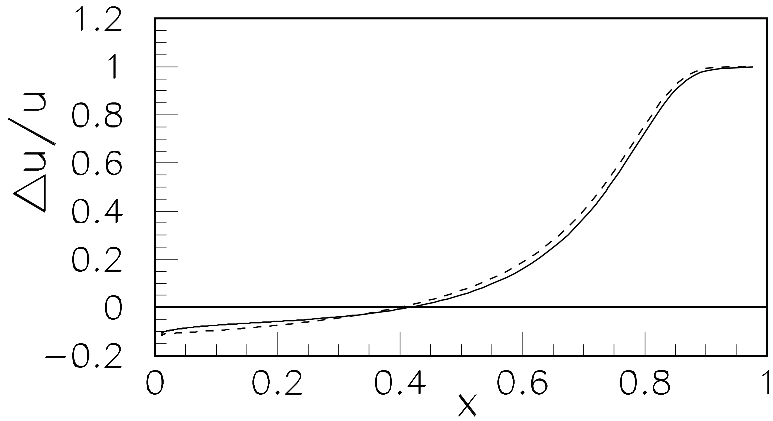

Figure 3: The ratio $\Delta u(x)/u(x)$ for the up and down valence quarks of the Λ in the SU(6) quark-diquark model. The solid and dotted curves are the corresponding results with (solid) and without (dotted) the Melosh-Wigner rotation.

such power-law behaviors of quark distributions, the ratio $d(x)/u(x)$ of the nucleon was predicted [6] to be 1/5 as $x \to 1$, and this gives $F_2^n(x)/F_2^p(x) = 3/7$, which is (comparatively) close to the quark-diquark model prediction 1/4. From the different power-law behaviors for parallel and anti-parallel quarks, one easily finds that $\Delta q/q = 1$ as $x \to 1$ for any quark with flavor q unless the q quark is completely negatively polarized [7]. Such prediction are quite different from the quark-diquark model prediction that $\Delta d(x)/d(x) = -1/3$ as $x \to 1$ for the nucleon [9, 10]. The most recent analysis [11] of experimental data for several processes supports the pQCD prediction of the unpolarized quark behaviors $d(x)/u(x) = 1/5$ as $x \to 1$, but there is still no definite test of the polarized quark behaviors $\Delta d(x)/d(x)$ since the d quark is the non-dominant quark for the proton and does not play a dominant role at large x.

We extend the pQCD analysis from the proton case to the Λ. From the SU(6) wave function of the Λ we get the explicit spin distributions for each valence quark,

$$\begin{array}{ll} u^{\uparrow} = d^{\uparrow} = \frac{1}{2}; & u^{\downarrow} = d^{\downarrow} = \frac{1}{2}; \\ s^{\uparrow} = 1; & s^{\downarrow} = 0. \end{array} \tag{34}$$

In pQCD and at large x, the anti-parallel helicity distributions can be neglected relative to the parallel ones, thus SU(6) is broken to $\mathrm{SU(3)}^{\uparrow} \times \mathrm{SU(3)}^{\downarrow}$. Nevertheless, the ratio $u^{\uparrow}/s^{\uparrow}$ is still 1/2 [7]. Thus helicity retention implies immediately that

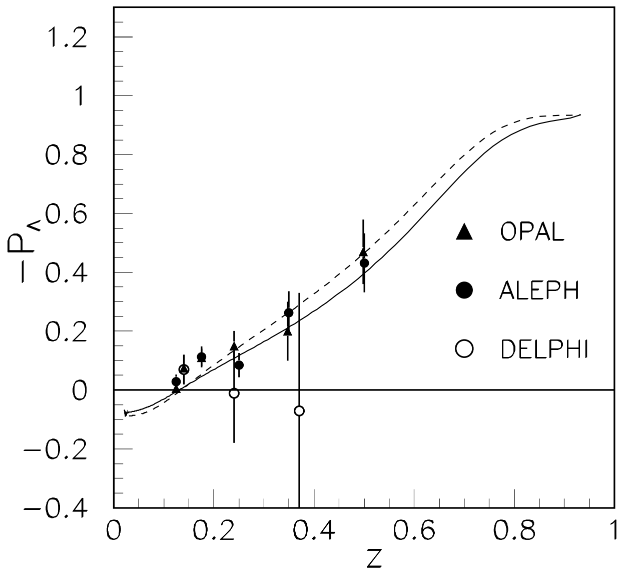

Figure 4: The comparison of the experimental data [30, 31, 32] for the longitudinal Λ-polarization P_Λ in e^+e^--annihilation process at the Z-pole with the theoretical calculations in the SU(6) quark-diquark model. The solid and dotted curves are the corresponding results with (solid) and without (dotted) the Melosh-Wigner rotation.

$u(x)/s(x) \to 1/2$ and $\Delta q(x)/q(x) \to 1$ (for $q = u$, d, and s) for $x \to 1$, and therefore the flavor structure of the Λ near $x = 1$ is a region in which accurate tests of pQCD can be made.

From the power-law behaviors of Eq. (32), we write down a simple model formula for the valence quark distributions,

$$q^{\uparrow}(x) \sim x^{-\alpha}(1-x)^3; \qquad q^{\downarrow}(x) \sim x^{-\alpha}(1-x)^5, \tag{35}$$

where $q^{\uparrow}(x)$ and $q^{\downarrow}(x)$ are the parallel and anti-parallel quark helicity distributions and α is controlled by Regge exchanges with $\alpha \approx 1/2$ for nondiffractive valence quarks. This model is not meant to give a detailed description of the quark distributions but to outline its main features in the large x region. We define $B_n = B(1/2, n+1)$ where $B(1/2, n+1)$ is the β-function defined by $B(1-\alpha, n+1) = \int_0^1 x^{-\alpha}(1-x)^n \mathrm{d}x$ for $\alpha = 1/2$. Combining Eq. (35) with Eq. (34), we get,

$$\begin{array}{ll} u^{\uparrow}(x) = d^{\uparrow}(x) = \frac{1}{2B_3}x^{-\frac{1}{2}}(1-x)^3; & u^{\downarrow}(x) = d^{\downarrow}(x) = \frac{1}{2B_5}x^{-\frac{1}{2}}(1-x)^5; \\ s^{\uparrow}(x) = \frac{1}{B_3}x^{-\frac{1}{2}}(1-x)^3; & s^{\downarrow}(x) = 0, \end{array} \tag{36}$$

which obviously satisfies that $u(x)/s(x) = 1/2$ and $\Delta q(x)/q(x) = 1$ (for $q = u$, d and s) as $x \to 1$, and it is easy to find that $B_3 = 32/35$ and $B_5 = 512/693$.

However, the above simple model satisfies the SU(6) quark model spin distributions, $\Delta s = 1$ and $\Delta u = \Delta d = 0$, and the spin sum $\Sigma\Delta q = 1$ which means that the helicity sum of the quarks equals to the Λ spin. From the nucleon case we know that this is not true in the real situation and the quark helicity sum is much more suppressed than the naive expectations from the famous "spin crisis" or "spin puzzle" [1, 3]. As emphasized in Ref. [37], the helicity distributions measured on the light-cone are related by the Melosh-Wigner rotation to the ordinary spins of the quarks in an equal-time rest-frame wave function description. Thus, due to the non-collinearity of the quarks, one cannot expect that the quark helicities will sum simply to the proton spin. From the SU(3) symmetry argument of Burkardt-Jaffe [13], we know that the s quark helicity $\Delta s = \int_0^1 \Delta s(x)\mathrm{d}x$ is suppressed from the simple quark model value 1 to $\Delta s \approx 0.6$ and the u and d quarks are also negatively polarized with quark helicities $\Delta u = \Delta d \approx -0.2$. The reduction in the quark helicities might be from sea quarks, but in this paper we simply assume that the Burkardt-Jaffe values of quark helicities can be attributed to the valence quarks, in order to amplify the effect due to the reduction of the quark helicity distributions in the valence quark region at large x (z). For this purpose we adopt a more general expression[†] for the quark distributions

$$\begin{aligned} &u^{\uparrow}(x) = d^{\uparrow}(x) = A_u x^{-\frac{1}{2}}(1-x)^3; \qquad && u^{\downarrow}(x) = d^{\downarrow}(x) = C_u x^{-\frac{1}{2}}(1-x)^5; \\ &s^{\uparrow}(x) = A_s x^{-\frac{1}{2}}(1-x)^3; && s^{\downarrow}(x) = C_s x^{-\frac{1}{2}}(1-x)^5, \end{aligned} \tag{37}$$

with the following parameters

$$\begin{aligned} A_u &= 0.4/B_3; \qquad & C_u &= 0.6/B_5; \\ A_s &= 0.8/B_3; & C_s &= 0.2/B_5, \end{aligned} \tag{38}$$

which are fixed by the constraints,

$$s = \int_0^1 s(x)\mathrm{d}x = 1; \qquad u = d = \int_0^1 u(x)\mathrm{d}x = 1, \tag{39}$$

[†]The coefficients A_q, B_q, C_q and D_q ($q = u, d, s$) in this section are different from those in section II.

which is exact for the valence quarks due to the quark number conservation, and

$$\Delta s = \int_0^1 \Delta s(x)\mathrm{d}x = 0.6; \qquad \Delta u = \Delta d = \int_0^1 \Delta u(x)\mathrm{d}x = -0.2, \tag{40}$$

which should be strictly true only for total quark contributions (valence+sea). We consider Eq. (37) as only a simplified model case in order to check the effect of the quark helicity suppression, but cannot be really true due to the absence of the sea contributions. We find that the SU(6) large-x relation

$$A_u = A_s/2 \tag{41}$$

is automatically satisfied for this case.

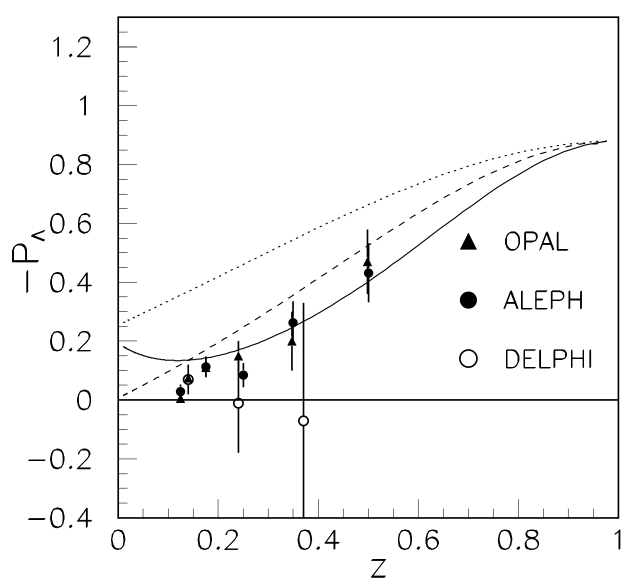

Figure 5: The comparison of the experimental data [30, 31, 32] for the longitudinal Λ-polarization P_Λ in e^+e^--annihilation process at the Z-pole with the theoretical calculations in the the pQCD analysis with three different cases: (a) case 1: the SU(6) quark-model spin distributions for the quark helicities, Eq. (36) (dotted curves); (b) case 2: the Burkardt-Jaffe values for the quark helicities, Eq. (37) (dashed curves) ; (c) case 3: the canonical form of quark distributions, Eq. (42) (solid curves).

In Fig. 5 we present the calculated Λ-polarization P_Λ for the above two simple cases of the pQCD analysis. For the case (case 1) of the naive SU(6) quark model spin distributions for the quark helicities, i.e., Eq. (36), we find that the absolute

magnitude is larger than the experimental data and also than the previous calculations [27, 28], which means that there should be a source to reduce the quark helicities. The large magnitude of P_Λ is due to the large positive contributions from u and d quarks, i.e., positive $\Delta u(x)$, at large x from the pQCD prediction. It is interesting to find that in the case of the Burkardt-Jaffe values of the valence quark helicities (case 2), i.e., Eq. (37), one can describe the data well but with a magnitude still slightly bigger, a result which is different from previous calculations [27, 28] in which the reduction in the quark helicities causes much smaller magnitudes of P_Λ than the data. This means that the reduction of quark helicities from the naive values of the SU(6) quark spin distributions should provide a more physical picture for the real world to describe the experimental data, contrary to previous conclusions [27, 28] that the naive SU(6) quark model predictions fit the data better.

In fact, the above two simple pQCD cases still suffer from the crudeness of the detailed shapes of the quark distributions with only the leading term contributions. For a better reflection of the complicated real situation we adopt the canonical form for the quark distributions, following Ref. [7],

$$\begin{aligned} u^\uparrow(x) = &\ d^\uparrow(x) = A_u x^{-\frac{1}{2}}(1-x)^3 + B_u x^{-\frac{1}{2}}(1-x)^4; \\ u^\downarrow(x) = &\ d^\downarrow(x) = C_u x^{-\frac{1}{2}}(1-x)^5 + D_u x^{-\frac{1}{2}}(1-x)^6; \\ s^\uparrow(x) = &\ A_s x^{-\frac{1}{2}}(1-x)^3 + B_s x^{-\frac{1}{2}}(1-x)^4; \\ s^\downarrow(x) = &\ C_s x^{-\frac{1}{2}}(1-x)^5 + D_s x^{-\frac{1}{2}}(1-x)^6. \end{aligned} \tag{42}$$

From the above constraints Eq. (39), we get

$$\begin{aligned} s &= A_s B_3 + B_s B_4 + C_s B_5 + D_s B_6 &= 1; \\ u &= A_u B_3 + B_u B_4 + C_u B_5 + D_u B_6 &= 1; \end{aligned} \tag{43}$$

where the β-functions $B_4 = 256/315$ and $B_6 = 2048/3003$. From Eq. (40), we get

$$\begin{aligned} \Delta s &= A_s B_3 + B_s B_4 - C_s B_5 - D_s B_6 &= 0.7; \\ \Delta u &= A_u B_3 + B_u B_4 - C_u B_5 - D_u B_6 &= -0.1, \end{aligned} \tag{44}$$

in which we have changed the valence quark helicities from the Burkardt-Jaffe values $\Delta s = 0.6$ and $\Delta u = -0.2$ to $\Delta s = 0.7$ and $\Delta u = -0.1$, to reflect the situation that the sea quarks might contribute partially to the total $\Delta s = 0.6$ and $\Delta u = -0.2$.

Combining with the SU(6) large-x relation (41) with Eqs. (43) and (44), we have only 5 constraints for the 8 parameters and there are still large degrees of freedom to adjust the parameters for a better fit of the Λ-polarization data. For example, we choose $A_u = 1/B_3$, $C_u = 2/B_5$, and $C_s = 2/B_5$ as inputs, and then have the following set of parameters:

$$\begin{aligned} &A_u = 1/B_3; \quad B_u = -0.55/B_4; \quad C_u = 2/B_5; \quad D_u = -1.45/B_6; \\ &A_s = 2/B_3; \quad B_s = -1.15/B_4; \quad C_s = 2/B_5; \quad D_s = -1.85/B_6, \end{aligned} \tag{45}$$

which is denoted as case 3. This case is not meant to be totally realistic but only to show that one can have a better description of the available P_Λ data with more reasonable picture for the flavor and spin structure of the Λ. We also present the results for this case in Figs. 5-8. The ratios $\Delta s(x)/s(x)$ and $\Delta u(x)/u(x)$ in this case have similar behaviors as those in the quark-diquark model with the Melosh-Wigner rotation effect. The calculated Λ-polarization P_Λ can also give a good description of the data at large z, as can be seen from Fig. 5, though the ratio of $u(x)/s(x)$ has the pQCD behavior rather than the quark-diquark type, as seen by comparing Fig. 6 with Fig. 1. For the three cases of pQCD analysis in our work, the ratios of $u(x)/s(x)$ for the unpolarized quark distributions, $\Delta s(x)/s(x)$ for the strange polarized quark distribution, and $\Delta u(x)/u(x)$ for the u and d polarized quark distributions are presented in Figs. 6-8. The quark momenta are also calculated for the three cases and we find:

$$\begin{aligned} &\langle x_u \rangle = \langle x_d \rangle = 0.094; \quad \langle x_s \rangle = 0.111; \quad \sum_q \langle x_q \rangle = 0.299, \quad \text{(case 1)} \\ &\langle x_u \rangle = \langle x_d \rangle = 0.091; \quad \langle x_s \rangle = 0.104; \quad \sum_q \langle x_q \rangle = 0.285, \quad \text{(case 2)} \\ &\langle x_u \rangle = \langle x_d \rangle = 0.118; \quad \langle x_s \rangle = 0.148; \quad \sum_q \langle x_q \rangle = 0.385. \quad \text{(case 3)} \end{aligned} \tag{46}$$

It is interesting to notice that the "most unlikely" scenario 3 in Ref. [28] is found to be better in reproducing the data. From our work we know that their scenario 3 with all flavor of quarks positively polarized is closer to our picture with $\Delta q(x)/q(x) = 1$ at $x \to 1$ for all quark flavors from the pQCD analysis, thus it is not strange that this scenario can give a better description of the data than the other two. But in the pQCD analysis the net quark helicities for the valence u and d quarks should be

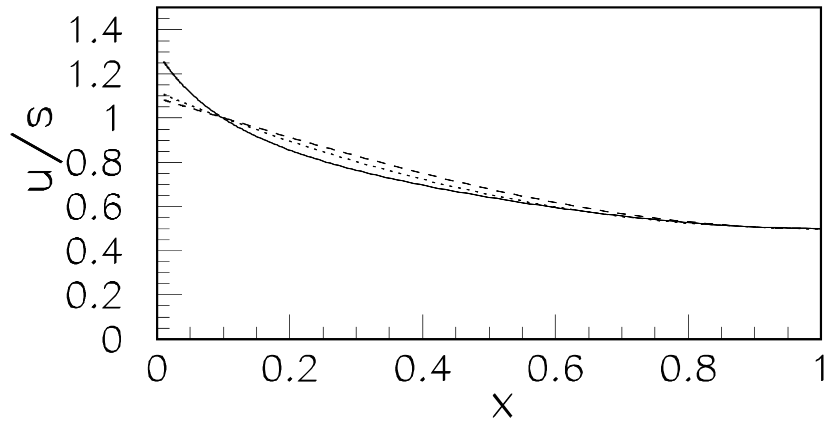

Figure 6: The ratio $u(x)/s(x)$ of the Λ in the pQCD analysis with three cases: case 1 (dotted curve); case 2 (dashed curve); and case 3 (solid curve).

zero or negative, which is different from their scenario 3 in which the u and d quark helicities are positive.

There are other contributions that need to be considered for a detailed description of the polarization. Those coming from sea quarks and gluons have not been considered in this work, and consequently the detailed features at small x in Figs. (4) and (5) should be unreliable. The contributions of those Λ's from the decay of other hyperons have been discussed and the corrections are found to be small [20, 27], therefore we can neglect them as a first approximation. In our work the connection between the quark distributions and the quark fragmentations should be only valid at low energy scale of around a few GeV. The evolution effects on the fragmentation functions have been analyzed in Ref. [26], and from re-producing the results in that work we notice that the evolution has a very small influence on the Λ polarization. Therefore the Λ polarization from e^+e^--annihilation near the Z-pole at the high energy scale does not alter the discussions concerning the Λ quark structure at the scale of our study. Of course, all these contributions deserve further study, along with the progress of the experimental precision and a deeper understanding concerning various quark to Λ fragmentations.

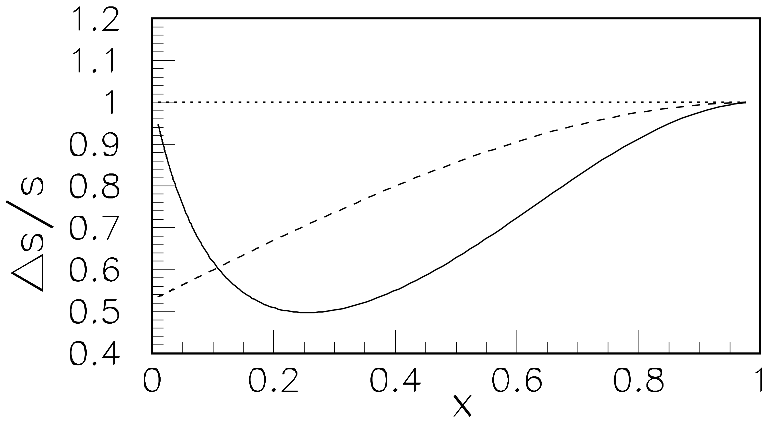

Figure 7: The ratio $\Delta s(x)/s(x)$ for the valence strange quark in the pQCD analysis with three cases: case 1 (dotted curve); case 2 (dashed curve); and case 3 (solid curve).

5 Discussions and Summary

From the above results in the paper, we found that the quark-diquark model gives a very good description of the available experimental data of the Λ-polarization in e^+e^--annihilation near the Z-pole. The pQCD analysis can also describe the data well by taking into account the suppression in the quark helicities compared to the naive SU(6) quark model spin distributions. Unfortunately, it is still not possible to make a clear distinction between the two different predictions of the flavor and spin structure of the Λ by only the Λ-polarization in e^+e^--annihilation near the Z-pole. This can be easily understood since the quark polarizations, $P_d = P_s = -0.94$ and $P_u = -0.67$, are close to each other, and the same behaviors of $\Delta s(x)/s(x)$, $\Delta u(x)/u(x)$, and $\Delta d(x)/d(x)$ near $x \to 1$ render it difficult to make a clean separation of the contributions from different flavors. Thus new information from other quantities related to the flavor and spin structure of the Λ are needed before we can have a clean distinction between different predictions, and it seems that Λ ($\overline{\Lambda}$) production in the neutrino (anti-neutrino) DIS processes [14] are more sensitive to different flavors.

In summary, we studied the flavor and spin structure of the Λ at large x in a pQCD analysis and in the quark-diquark model, and then applied the results to discuss the

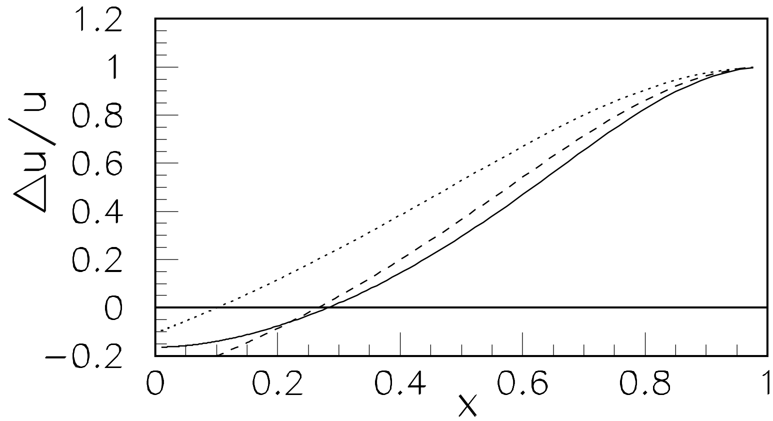

Figure 8: The ratio $\Delta u(x)/u(x)$ for the up and down valence quarks of the Λ in the pQCD analysis with three cases: case 1 (dotted curve); case 2 (dashed curve); and case 3 (solid curve).

Λ-polarization of Λ production in e^+e^--annihilation process near the Z-pole. We found that the two theoretical frameworks give better description of the available experimental data than previous calculations and also provide more a reasonable picture, close to the real situation. Thus the results in this paper can be considered as a phenomenological support to our prediction [15] that the u and d quarks should be positively polarized at large x, even though their net helicities might be zero or negative. More attention, both theoretically and experimentally, is needed to study the flavor and spin structure of the Λ for the purpose of making a clear distinction between different predictions.

Acknowledgments: This work is partially supported by National Natural Science Foundation of China under Grant No. 19605006, No. 19975052, and No. 19875024, and by Fondecyt (Chile) postdoctoral fellowship 3990048, by Fondecyt (Chile) grant 1990806 and by a Cátedra Presidencial (Chile).

References

[1] For reviews, see, e.g., H.-Y. Cheng, Int. J. Mod. Phys. **A 11**, 5109 (1996); G.P. Ramsey, Prog. Part. Nucl. Phys. **39**, 599 (1997).

[2] For a recent review, see, e.g., S. Kumano, Phys. Rep. **303**, 183 (1998).

[3] S.J. Brodsky, J. Ellis, and M. Karliner, Phys. Lett. **B 206**, 309 (1988); J. Ellis and M. Karliner, Phys. Lett. **B 213**, 73 (1988); **B 341**, 397 (1995).

[4] See, e.g., S.J. Brodsky and B.-Q. Ma, Phys. Lett. **B 381**, 317 (1996), and references therein.

[5] B.-Q. Ma, Phys. Lett. **B 274**, 111 (1992); C. Boros, J.T. Londergan, and A.W. Thomas, Phys. Rev. Lett. **81**, 4075 (1998).

[6] G.R. Farrar and D.R. Jackson, Phys. Rev. Lett. **35**, 1416 (1975).

[7] S.J. Brodsky, M. Burkardt, and I. Schmidt, Nucl. Phys. **B 441**, 197 (1995).

[8] R. Carlitz, Phys. Lett. **B 58**, 345 (1975); J. Kaur, Nucl. Phys. **B 128**, 219 (1977); A. Schäfer, Phys. Lett. **B 208**, 175 (1988).

[9] B.-Q. Ma, Phys. Lett. **B 375**, 320 (1996).

[10] W. Melnitchouk and A.W. Thomas, Phys. Lett. **B 377**, 11 (1996).

[11] U.K. Yang and A. Bodek, Phys. Rev. Lett. **82**, 2467 (1999).

[12] SM Collab., B. Adeva *et al.*, Phys. Lett. **B 369**, 93 (1996); **B 420**, 180 (1998).

[13] M. Burkardt and R.L. Jaffe, Phys. Rev. Lett. **70**, 2537 (1993).

[14] B.-Q. Ma and J. Soffer, Phys. Rev. Lett. **82**, 2250 (1999).

[15] B.-Q. Ma, I. Schmidt, and J.-J. Yang, USM-TH-77, hep-ph/9906424.

[16] See, e.g., R.L. Jaffe and X. Ji, Phys. Rev. Lett. **71**, 2547 (1993).

[17] V.N. Gribov and L.N. Lipatov, Phys. Lett. **B 37**, 78 (1971); Sov. J. Nucl. Phys. **15**, 675 (1972).

[18] See, e.g., DASP Collab., R. Brandelik *et al.*, Nucl. Phys. **B 148**, 189 (1979); T. Kawabe, Prog. Theor. Phys. **65**, 1973 (1981).

[19] S.J. Brodsky and B.-Q. Ma, Phys. Lett. **B 392**, 452 (1997).

[20] G. Gustafson and J. Häkkinen, Phys. Lett. **B 303**, 350(1993).

[21] W. Lu and B.-Q. Ma, Phys. Lett. **B 357**, 419 (1995);
W. Lu, Phys. Lett. **B 373**, 223 (1996).

[22] J. Ellis, D. Kharzeev, and A. Kotzinian, Z. Phys. **C 69**, 467 (1996);
M. Alberg, J. Ellis, and D. Kharzeev, Phys. Lett. **B 356**, 113 (1995).

[23] R.L. Jaffe, Phys. Rev. **D 54**, R6581 (1996).

[24] M. Anselmino, M. Boglione, J. Hansson, and F. Murgia, Phys. Rev. **D54**, 828 (1996).

[25] A. Kotzinian, A. Bravar, and D.von Harrach, Eur. Phys. J. **C 2**, 329 (1998).

[26] D.de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. **81**, 530 (1998).

[27] C. Boros and Z. Liang, Phys. Rev. **D 57**, 4491 (1998).

[28] D.de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. **D 57**, 5811 (1998).

[29] For proposals related to transversely polarized Λ hyperons, see, e.g.,
W. Lu, Phys. Rev. **D 51**, 5305 (1995);
Z. Liang and C. Boros, Phys. Rev. Lett. **79**, 3608 (1997);
D.de Florian, J. Soffer, M. Stratmann, and W. Vogelsang, Phys. Lett. **B 439**, 176(1998).

[30] ALEPH Collaboration, D. Buskulic *et al*, Phys. Lett. **B 374**, 319 (1996).

[31] DELPHI Collaboration, Report No.DELPHI 95-86 PHYS 521, CERN-PPE-95-172, presented at the EPS-HEP 95 conference, Brussels, 1995.

[32] OPAL Collaboration, K. Ackerstaff *et al*, Eur. Phys. J. **C 2**, 49 (1998).

[33] See, e.g., S. J. Brodsky and G. P. Lepage, in *Perturbative Quantum Chromodynamics*, edited by A. H. Mueller (Singapore, World Scientific, 1989), p. 93.

[34] S.J. Brodsky, H.-C. Pauli, and S.S. Pinsky, Phys. Rep. **301**, 299 (1998).

[35] S. J. Brodsky, T. Huang, and G. P. Lepage, in *Particles and Fields-2*, Proceedings of the Banff Summer Institute, Banff, Alberta, 1981, edited by A. Z. Capri and A. N. Kamal (Plenum, New York,1983), p. 143.

[36] S.J. Brodsky and F. Schlumpf, Phys. Lett. **B 329**, 111 (1994).

[37] B.-Q. Ma, J. Phys. **G 17**, L53 (1991);

B.-Q. Ma and Q.-R. Zhang, Z. Phys. **C 58**, 479 (1993).

[38] B.-Q. Ma, I. Schmidt, and J. Soffer, Phys. Lett. **B 441**, 461 (1998);

B.-Q. Ma and I. Schmidt, Phys. Rev. **D 58**, 096008 (1998).

[39] M. Nzar and P. Hoodbhoy, Phys. Rev. **D 51**, 32 (1995).

[40] C. Boros and A.W. Thomas, hep-ph/9902372, to be published in Phys. Rev. **D** (1999); C. Boros, J.T. Londergan, and A.W. Thomas, hep-ph/9908260.

[41] R. Blankenbecler and S.J. Brodsky, Phys. Rev. **D 10**, 2973 (1974); J.F. Gunion, Phys. Rev. **D 10**, 242 (1974); S.J. Brodsky and G.P. Lepage, in Proc. 1979 Summer Inst. on Particle Physics, SLAC (1979).